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SONAR SURVEILLANCE THROUGH A NORTH PACIFIC OCEAN FRONT (U)

JA Neubert

June 1981

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20. ABSTRACT *(Continue on reverse side II necessary and identify by block number)*

(U) This report considers the problem of detecting long-range, low-frequency, narrowband CW sources for sound transmission through ocean fronts. Sound propagation through the subarctic sound-speed front north of Hawaii was studied using PARKA I data. A new stochastic model of sound intensity was applied to the PARKA I front. This model introduces two new stochastic factors that modify deterministic sound propagation. Comparison of the stochastic with the deterministic sound intensity model showed that the two stochastic factors were necessary to account for sound propagation behavior in the frontal region. These stochastic factors showed that horizontal frontal sound-speed gradients have a pronounced effect upon the propagation of sound and, hence, the masking of sources by ocean fronts. Suggestions for measurements to better understand the masking of sources by fronts in the deep ocean are given.

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CONTENTS (U)

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I INTRODUCTION (U)

(C) Soviet submarine contacts are presently being lost intermittently in the North Pacific Ocean. This is especially true of Soviet submarines transiting west of Japan and being observed from SOSUS stations near Midway (see Fig 1). Therefore, it is important to analyze the problem of detecting long-range, low-frequency, narrowband CW sources for acoustic transmission across oceanographic transition regions. Sound propagation through the subarctic sound-speed front north of Hawaii was studied using PARKA I data. A new stochastic model of sound intensity was applied to the PARKA I front. This model introduces two new stochastic factors that modify deterministic sound propagation relations. Comparison of the stochastic with the deterministic sound intensity model showed that the two stochastic factors were necessary to account for sound propagation behavior in the frontal region. These stochastic factors showed that horizontal frontal sound-speed gradients have a pronounced effect upon the propagation of sound and, hence, the masking of sources by ocean fronts.

(U) In designing and modeling sonar surveillance systems for arrays it is important to consider the environmental acoustic factors (such as ocean fronts and eddies) that generate variability in system performance. The environmental factors acting upon acoustic signals that are received by these arrays result in variable outputs from these systems. For single array systems, the array gain and beamforming are adversely affected. Two methods that have been used to treat this problem are (1) a Monte Carlo variation of the various terms in the sonar equation and (2) a detailed modeling of the specific physical source of the fluctuations and variations (such as internal waves) that interact with the acoustic signal. The first method usually involves *ad hoc* estimates of the spread of variability of each term in the sonar equation, while the second method is dependent on having a detailed model of the sources of the environmental acoustic factors. Unfortunately, such a detailed physical model is not generally available for all oceanic regions and phenomena of interest. Therefore, a middle approach is advisable, in which the sound-speed fluctuations and variations are allowed to perturb the signal progressively as it propagates, but the specific nature of the causes of these signal distortions and variability is not assumed. Instead, the stochastic measure of these signal perturbations is taken by expressing the signal relations in terms of decorrelation lengths. The parameters are then evaluated analytically and/or determined empirically by averaging actual sound propagation data without assuming the specific physical phenomena that produce the environmental acoustic factors.
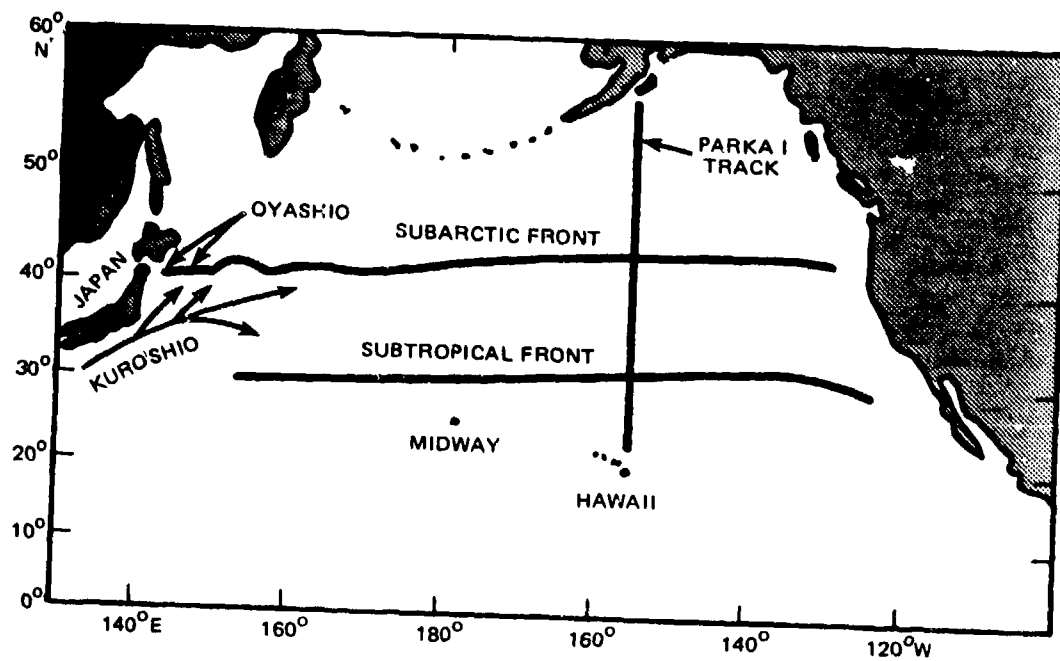
(U) In this report the middle approach is summarized in the Appendix as developed in Ref 1 from an earlier and less complete model (ref 2, 3). The major relations of this analytic approach are discussed in Section III.

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[1] J. A. Neubert, "A mean multipath relation for sound propagation through a random ocean front" (in preparation).

[2] J. A. Neubert, "Multipath summability intensity calculations in the real ocean," J. Acoust. Soc. Am. 51, 310–322 (1972).

[3] J. A. Neubert, "Experimental agreement of stochastic ray-theory relations," J. Acoust. Soc. Am. 62, 326–334 (1977).

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(U) Figure 1. PARKA I track and the main North Pacific oceanic fronts.

II. EXPERIMENTAL DESCRIPTION (U)

(C) Figure 1 shows the subarctic sound-speed front, which is more pronounced and erratic near Japan (where strong and irregular eddies are present). This front extends (at about 41°N latitude) across the North Pacific Ocean and becomes reasonably stable north of Hawaii, where it intersects the PARKA I track. The PARKA I (Pacific Research Kaneohe-Alaska) track runs northward from near Hawaii (22°N, 157° 20'W) to near Alaska (55°N, 157°20'W). Figure 2 summarizes the acoustic environment along the PARKA I measurement track. The REXBURG towed a thermistor chain from 41 to 45°N to survey the sound-speed structure of the subarctic front. For more detailed information on the PARKA I experiment see Ref. 4 and 5 as well as the following discussion.

(C) The FLIP was nominally located at 27°20'N, 157°20'W and served as the receiver platform for the 178-Hz CW source that was towed northward at 10 knots by the RADFORD at a depth of 500 ft along the PARKA I measurement track. The test geometry for the hydrophone chain suspended from the FLIP is shown in Fig 3. The CW tow and its concurrent oceanographic measurements occurred between 27 August and 5 September 1968. The source level was kept constant at 102 dB//μbar @ 1 yd throughout the CW PARKA I tow. The acoustic receiving system for the projector signals employed a 1-Hz-wide bandpass centered at the 178-Hz CW tone.

(C) Much effort was devoted to applying Raywave (Ref 6) to the PARKA I environmental data to obtain coherent and incoherent values for the intensity along the total 1500-nmi PARKA I measurement track. This included obtaining the Raywave environment input data, ie, sound-speed profiles (Ref 7), bottom topography (Ref 8) and bottom loss coefficients. The sound-speed profile in the deep ocean, below 2500 m, was found to be very constant, both in time and distance, over the PARKA I track. The bottom reflection curve for 500 Hz of Ref 4 was used since it agreed well with the data used in this study. The computed intensities for regions between covergence zones are influenced somewhat by bottom-reflected paths, while convergence zones are not. In general, there were few bottom-bounce paths of any significance in this study. The attenuation co-efficient was obtained from Ref 9. The received intensity at FLIP for the 178-Hz tone decreased gradually with increasing range as the rising deep channel axis, which ducts the sound propagation (see Fig 2), and decreasing surface temperature, which augments the duct, acted to reduce the interaction of the propagated energy with the bottom.

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4 The PARKA I Experiment (U), Maury Center for Ocean Science, MC Report 003, Vol. 1, Nov. 1969 (Secret).

5 Appendices for the PARKA I Experiment (U), Maury Center for Ocean Science, MC Report 003, Vol. 2, Jan. 1971 (Confidential).
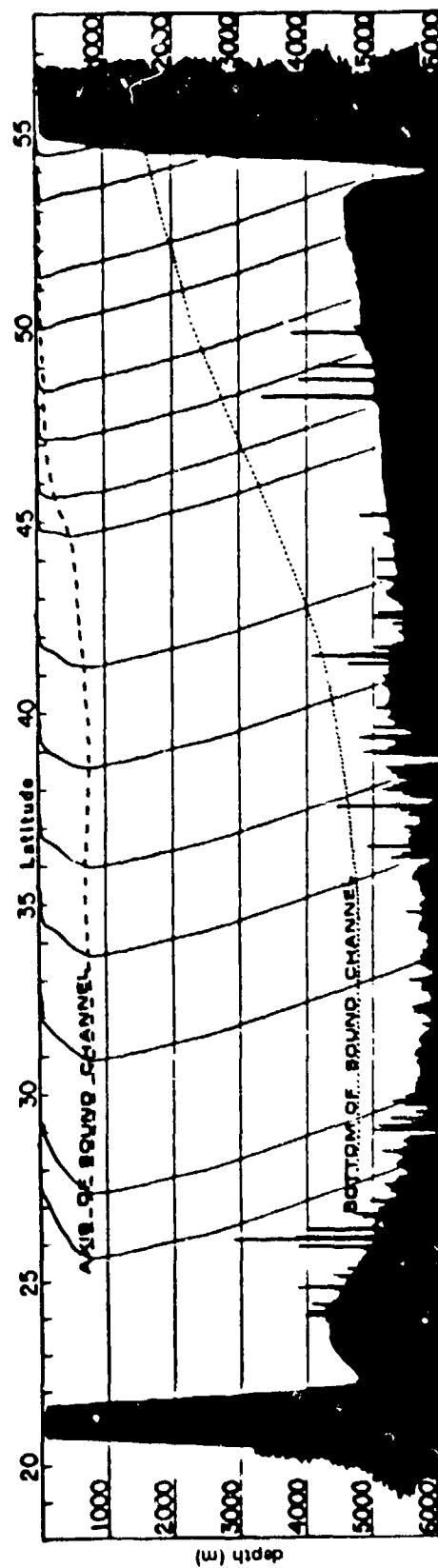
6 W. H. Watson and R. W. McGirr, "Raywave II: A Propagation Loss Model for the Analysis of Complex Ocean Environments," NUC TN 1516, 1975.

7 Personal communication with Paul Bucca of NORDA.

8 Personal communication with Dr. J. D. Northrop of NOSC.

9 J. R. Lovett "Geographic variation of low-frequency sound absorption in the Pacific Ocean," J. Acoust. Soc. Am. 65, 253-254 (1979).
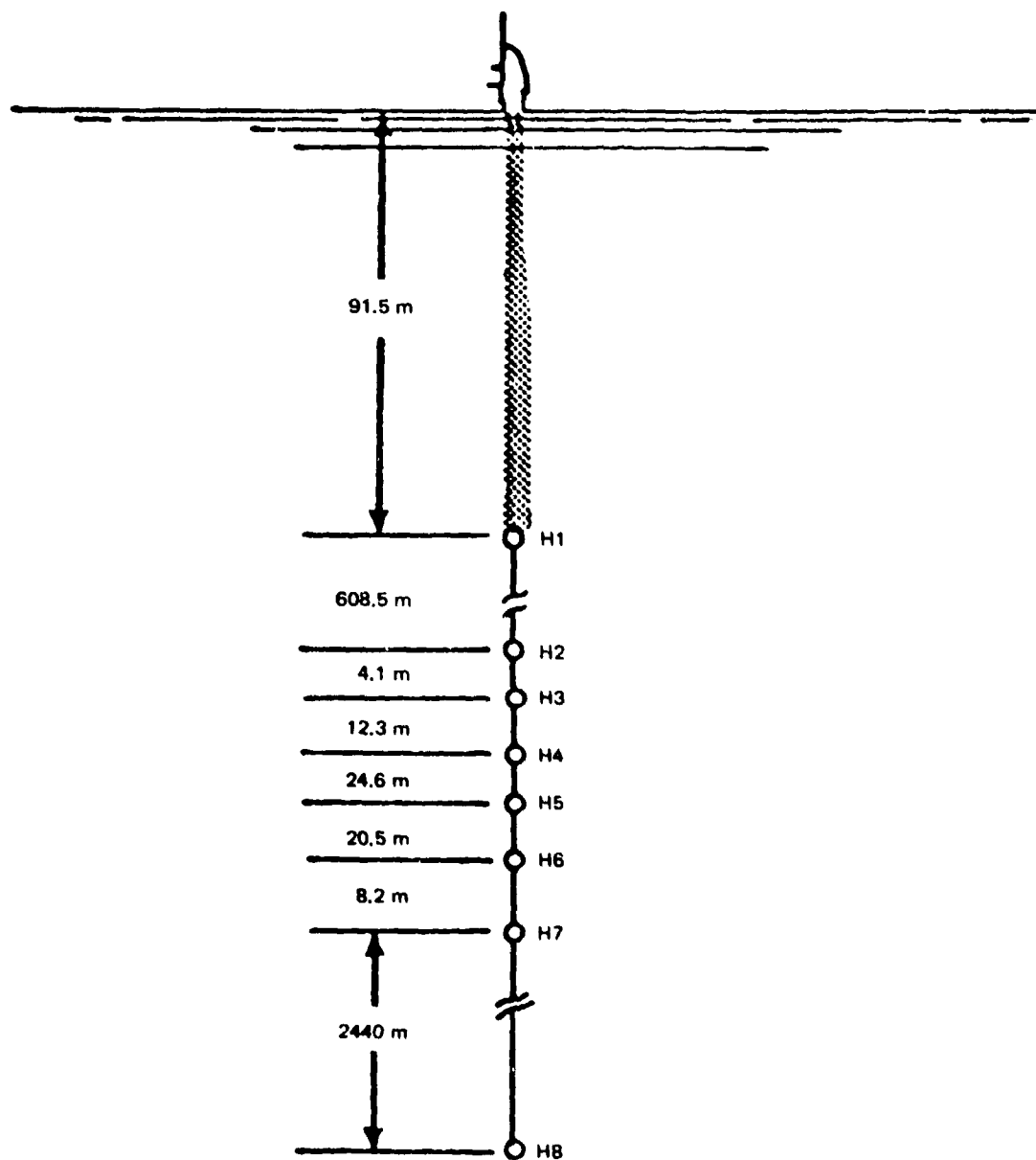
(U) Figure 2. PARKA I acoustic environment.

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91.5 m

H1

608.5 m

H2

4.1 m

H3

12.3 m

H4

24.6 m

H5

20.5 m

H6

8.2 m

H7

2440 m

H8

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(U) Figure 3. FLIP hydrophone system geometry.

III. ANALYTICAL STUDY (U)

(U) In the Appendix the stochastic relations of Ref 1 are reviewed for the purpose of this study of sound propagation through an ocean front. These analytic relations are summarized below. The theoretical mean intensity relation is given by

$$E\left|I(\underline{x})\right| \doteq \sum_{m=1}^{M} I_0(s_m)\left[F_0(s_m)\,F_i(s_m)\right]$$

$$+ 2\sum_{m=1}^{M-1}\sum_{\ell=m+1}^{M} I_0^{1/2}(s_m)\,I_0^{1/2}(s_\ell)\left[F_0^{1/2}(s_m)\,F_0^{1/2}(s_\ell)\,F_i^{1/2}(s_m)\,F_i^{1/2}(s_\ell)\right]$$

$$\cdot F_p(s_m)\,F_p(s_\ell)\cos\left[k_0\left(S_{om}-S_{o\ell}\right)\right]\ , \tag{1}$$

where Eq (1) has been separated into autopath terms (which gives the incoherent intensity) and crosspath terms (which gives the coherent contribution to the mean intensity). In Eq (1) M is the toal number of received paths, s_m is the arc length of ray path m, $E\{I(\underline{x})\}$ is the mean intensity I at point $\underline{x}$, I_0 (sm) is the Raywave computed (deterministic) intensity, $F_p(s)$ is the partial coherence factor of Eq (A-8), $F_0(s)$ is the stochastic scatter loss factor of Eq (A-4), which is dependent on the horizontal sound-speed gradient [see Eq (A-9)], $F_i(s)$ is the stochastic gain factor of Eq (A-6) which is dependent on the horizontal sound-speed [see Eq (A-10)], and S_0 is the deterministic phase factor of Eq (A-3).

(U) In passive surveillance applications, the system threshold is determined by $E\{I\}$ and the standard deviation about $E\{I\}$, where

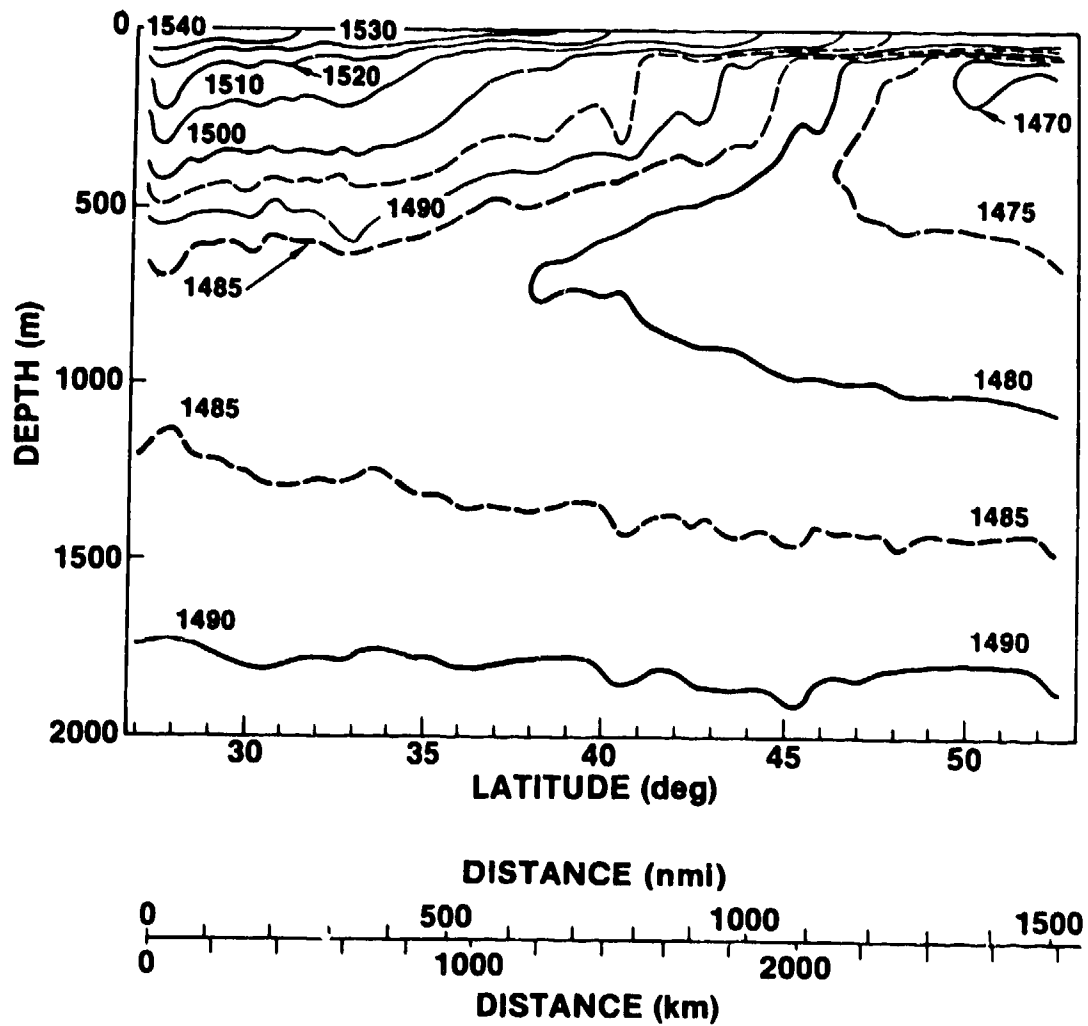$$\sigma_I \doteq \sum_{m=1}^{M} I_0(s_m)\,F_0(s_m)\,F_i(s_m)\left[1-F_p^{\,2}(s_m)\right]\ .$$

IV. RESULTS (U)

(C) In Eq (1) and (2) the stochastic factors $F_o(s)$ and $F_i(s)$ were introduced. These stochastic factors are dependent on the horizontal sound-speed gradients [see Eq (A-9) and (A-10)] but not the frequency [see Eq (A-4) and (A-6)]. The question is how strong do these gradients have to be to produce decorrelation lengths that are significant for passive surveillance operations. Figure 4 shows a sharp but shallow (less than 900 ft) horizontal sound-speed gradient near 41°N along the FARKA I track. Figure 5 shows the PARKA I propagation loss data for three FLIP hydrophones. Figure 5a shows that the shallow (300 ft) receiver intensity is reduced (about 5 to 10 dB) near 41°N (but only in the region of the rapid horizontal sound-speed gradient) and continues essentially level (but more variable) thereafter. Thus, the sound-speed front reduces the receiver intensity significantly and the stochastic factors $F_o(s)$ and $F_i(s)$ model this pronounced effect upon the propagation of sound through an ocean front. Figure 5b represents the receiver depth for SOSUS application (2500 ft), but the intensity does not indicate any influence from the front. This is probably due to the shallowness of the front relative to the source depth and the strong ducting of sound near the deep channel axis. It is possible that targets shallower than 500 ft would also be masked for SOSUS-depth surveillance arrays. Figure 5c represents the FLIP receiver at 10,800 ft and has the appearance of deep received sound with no sign of a front.

(U) The Raywave (incoherent) intensity for the deep sound channel FLIP receiver is shown in Fig 6. Agreeing with Fig 5b, it shows no perturbation ascribable to the front near 41°N on the PARKA I track when the source is deep enough. (This may not be the case for sufficiently shallow sources.) The Raywave (incoherent) intensity for the shallow FLIP receiver is shown in Fig 7 and, in contrast to Fig 5a, shows no reduction ascribable to the front near 41°N on the PARKA I track. Therefore, the deterministic ray theory (Fig 7) does not account for the reduction in sound intensity observed in the data (Fig 5a). However, $F_o(s)$ and $F_i(s)$ in Eq (1) act like strong stochastic perturbations of the deterministic ray theory intensity in the narrow region of the sharp sound-speed frontal gradients and are needed to explain the influence of the front on sound propagation for passive surveillance arrays. This indicates that $F_o(s)$ and $F_i(s)$ are of practical significance in Eq (1) only in the frontal regions, where strong horizontal sound-speed gradients exist.

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(U) Figure 4. PARKA I sound-speed contours.
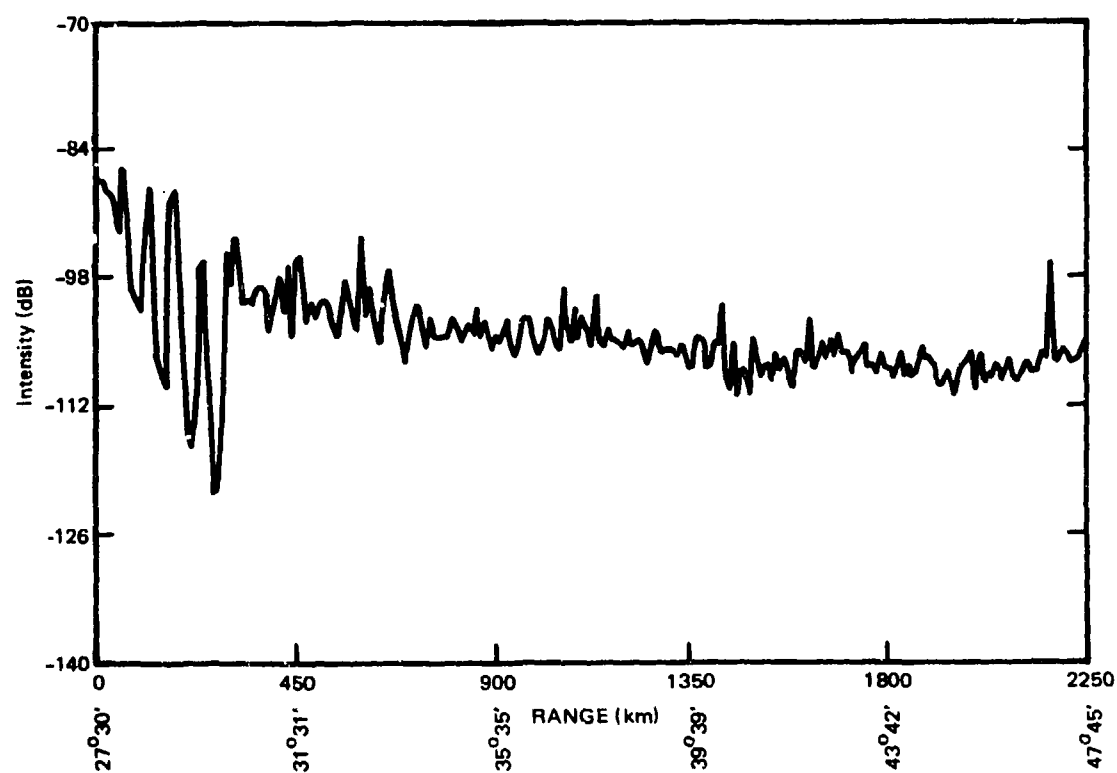
(C) Figure 5. PARKA I propagation loss data. Source CW projector 500 ft; frequency 178 Hz.

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(C) Figure 6. Incoherent (Raywave) intensity for PARKA I; source at 500 ft, receiver at 2500 ft, 178-Hz CW tone.

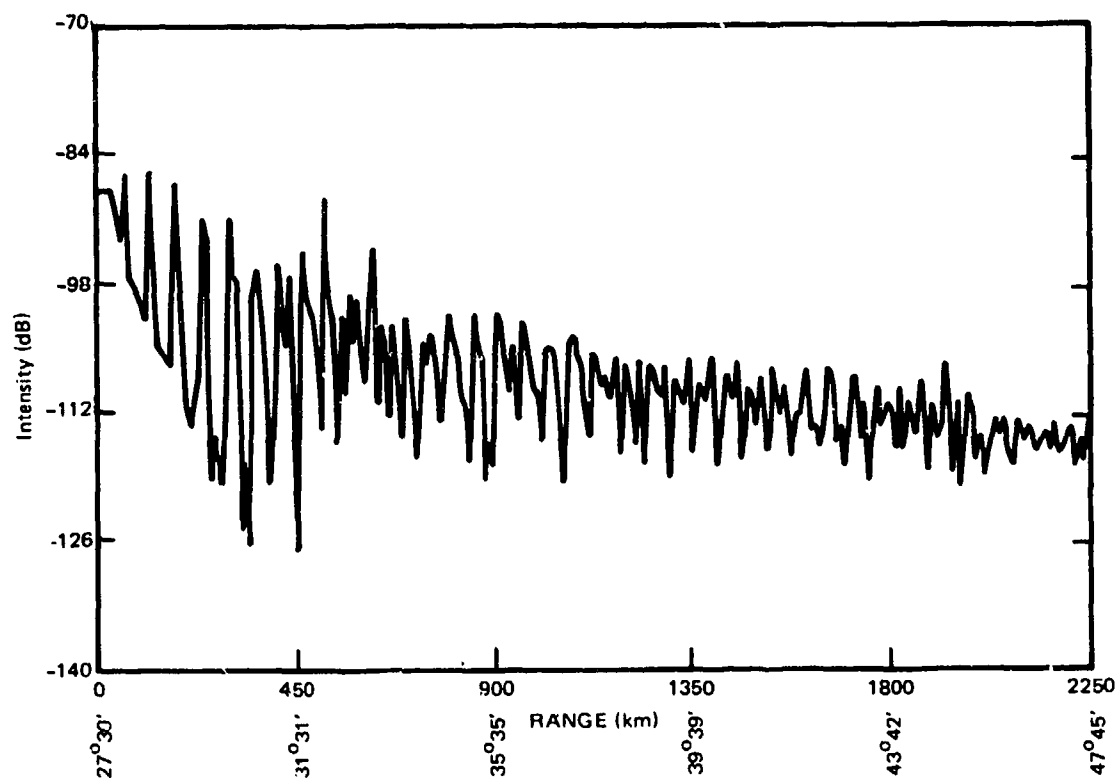(UNCLASSIFIED)

(C) Figure 7. Incoherent (Raywave) intensity for PARKA I; source at 500 ft, receiver at 300 ft, 178-Hz CW tone.

V. CONCLUSIONS (U)

(U) Comparison of stochastic with deterministic sound intensity analysis showed that two stochastic factors, $F_o(s)$ and $F_i(s)$, were necessary to account for the masking of a target by a front. These stochastic factors showed that the strength of the horizontal frontal sound-speed gradient, but not the source frequency, determines the masking of targets by fronts. For the PARKA I experiment it was found that when both the receiver (at 300 ft) and the source (at 500 ft) were above the depth (about 900 ft) of the horizontal sound-speed front, the source was masked by the front. However, receivers at much greater depths did not indicate any significant source masking. This was especially true for the 2500-ft receiver (near the sound channel axis), where the sound was strongly ducted. Therefore, when attempting to observe targets from behind a front, it is important to keep the receiving array very deep (preferably near or below the deep sound channel axis). It remains to be determined if even shallower targets near, but behind, the front can avoid enough sound ducting to significantly mask targets for deeper arrays. In fact, hiding the target in or behind the frontal region may also be a highly effective source-masking tactic. At least four parameters (and their interaction) need to be better understood in determining the masking of sources by fronts in the deep ocean. These are the effects of (1) the strength and depth of the front, (2) the depth of the array, (3) the depth of the source (relative to the depth of the front) and its nearness to the front, and (4) the strength of the sound duct necessary to overcome masking of the source by the front. (The range from the array to the front is an important factor for this latter parameter.)

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1   J. A. Neubert, "A mean multipath relation for sound propagation through a random ocean front" (in preparation).

2   J. A. Neubert, "Multipath summability intensity calculations in the real ocean," J. Acoust. Soc. Am. 51, 310-322 (1972).

3   J. A. Neubert, "Experimental agreement of stochastic ray-theory relations," J. Acoust. Soc. Am. 62, 326-334 (1977).

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11   J. A. Neubert and J. L. Lumley, "Approach to stochastic Lagrangian integrals and their asymptotic evaluation for sound propagation in continuous stochastic media," J. Math. Phys. 13, 164–183 (1972).

12   J. A. Neubert, "Steady-state sound propagation in continuous, statistically isotropic media," J. Math. Phys. 13, 1511–1524 (1972).

13   J. A. Neubert and J. L. Lumley, "The nature of sound fluctuation in the upper ocean. II," J. Acoust. Soc. Am. 64, 1148-1158 (1978).

APPENDIX (U)

(U) In Ref 2 the effect of the phase fluctuations on the mean multipath ray theory intensity was developed. This resulted in the introduction of an important stochastic factor which is called the "partial coherence factor." In Ref 1 the amplitude fluctuation behavior was retained as well; this resulted in two new stochastic factors that are crucially important in sound propagation through an ocean front.

(U) As in Ref 1, the notation is as follows. The refractive index n is represented by

$$n = n[\underline{X}(s)] = n_0[X(s)][1 + \alpha u(s)] = c_0/c[\underline{X}(s)],$$ (A-1)

where c_0 is some convenient reference sound speed, $c[\underline{X}(s)]$ is the sound speed at path arc length s at point $\underline{X}$, $\underline{X}(s)$ varies from its initial point $\underline{X}(s=o) = \underline{\xi}$ to its terminal point $\underline{x}$, αu are the fluctuation of n about its mean value $n_0 = <n>$, and α ($0 < \alpha << 1$) is the normalized rms intensity of the refractive index fluctuations.

(U) In Ref 1 the stochastic integral theory of Ref 2 and 10 through 13 was applied to produce the mean multipath intensity relation

$$E\{I(x)\} \doteq \sum_{m=1}^{M} I_0(s_m) F_0(s_m) F_i(s_m)$$

$$+ 2 \sum_{m=1}^{M-1} \sum_{\ell=m+1}^{M} I_0^{1/2}(s_m) I_0^{1/2}(s_\ell) F_0^{1/2}(s_m) F_0^{1/2}(s_\ell) F_i^{1/2}(s_m) F_i^{1/2}(s_\ell)$$

$$\cdot F_p(s_m) F_p(s_\ell) \cos[k_0(S_{om} - S_{o\ell})].$$ (A-2)

where

$$S_0 \equiv \int_0^s ds' \, n_0 \, \underline{X}(s')$$ (A-3)

is the deterministic phase factor, k_0 is the wavenumber,

$$F_0(s) = \exp\left(-2\alpha^2 R_{a3} Q_3 s^2\right) = \exp\left(-s^2/d_0^2\right)$$ (A-4)

10 J. A. Neubert, "Approach to the Eulerian–Lagrangian problem for sound propagation in continuous stochastic media." J. Math. Phys. 12; 1030–1034 (1971).

11 J. A. Neubert, and J. L. Lumley, "Approach to stochastic Lagrangian integrals and their asymptotic evaluation for sound propagation in continuous stochastic media," J. Math. Phys. 13, 164–183 (1972).

12 J. A. Neubert, "Steady-state sound propagation in continuous, statistically intropic media," J. Math. Phys. 13, 1511–1524 (1972).

13 J. A. Neubert and J. L. Lumley, "The nature of sound fluctuation in the upper ocean. II," J. Acoust. Soc. Am. 64, 1148–1158 (1978).

with the decorrelation length

$$d_o \equiv \left(\alpha \sqrt{2 R_{a3} Q_3} \right)^{-1} \tag{A-5}$$

is the stochastic scatter loss factor [it represents the scattering away of acoustic energy and is dependent on the sound-speed gradients as shown in Eq (A-9)],

$$F_i(s) \equiv \exp\left(2\alpha^2 R_{a1} Q_1 s \right) = \exp\left(s/d_i \right) \tag{A-6}$$

with decorrelation length

$$d_i \equiv \left(2\alpha^2 R_{a1} Q_1 \right)^{-1} \tag{A-7}$$

is the stochastic scatter gain factor [it represents the scattering in of acoustic energy and is dependent on the sound-speed gradients as shown in Eq (A-10)],

$$F_p(s) \equiv \exp\left(-2\alpha^2 k_o^2 L s \right) \tag{A-8}$$

is the partial coherence factor [it gives the decrease in the coherent crosspath term in Eq (A-2)],

$$4s^2 R_{a3} Q_3 \sim \int_0^s ds' \int_0^s ds'' \int_0^s ds'' \, n_o(\underline{\xi}) \frac{dX_i}{ds}(0) \, E\left\{ u'_{,i}(s') \right.$$
$$\left. \cdot \left[u'_{,jj}(s''', s'') - E\left\{ u'_{,jj}(s''', s') \right\} \right] \right\} , \tag{A-9}$$

$$4s R_{a1} Q_1 \sim \int_0^s ds' \int_0^s ds'' \, n_o^2(\underline{\xi}) \, E\left\{ u'_{,i}(s') \, u'_{,i}(s'') \right\} , \tag{A-10}$$

$$4sL \sim \int_0^s ds' \int_0^s ds'' \, n_o(s') \, n_o(s'') \, E\left\{ \left[u(s') - E\{ u(s') \} \right] \right.$$
$$\left. \cdot \left[u(s'') - E\{ u(s'') \} \right] \right\} , \tag{A-11}$$

$$u'_{,i}(s') \equiv \left[\frac{u(s')}{n_o(s')} \right]_{,i} \tag{A-12}$$

and

$$u'_{,\,ii}(s'',\,s') \equiv \left[u,_{i}(s'')\,\frac{n_o(s'')}{n_o(s')} \right]_{,i}$$
(A-13)

(U) In a similar manner the standard deviation σ_I about $E\{I\}$ was evaluated in Ref 1 to give

$$\sigma_I \simeq \sum_{m=1}^{M} I_o(s)\,F_o(s_m)\,F_i(s_m)\left[1 - F_p^{\,2}(s_m)\right] \ .$$
(A-14)

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Encl: (1) Listing of Known Classified PARKA Reports

1. In response to reference (a), the Chief of Naval Operations (N874) has reviewed a number of Pacific Acoustic Research Kaneohe-Alaska (PARKA) Experiment documents and has determined that all PARKA I and PARKA II reports may be declassified and marked as follows:

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(NUSC NL Accession # 057708)

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√(DTIC # 529 945)

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(NUSC NL Accession # 004943)

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(DTIC # C034 016)

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